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Toxic *Prymnesium parvum*: A Potential Threat to U.S. Reservoirs

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Abstract.—*Prymnesium parvum*, the golden alga, is a toxin-producing, microscopic alga first identified in U.S. inland waters during a 1985 fish kill on the Pecos River, Texas. Golden alga has been reported in 16 states, and toxic blooms have caused substantial fish kills and loss to recreation. Golden alga releases toxins (prymnesins) that affect gill-breathing organisms but do not affect most aquatic insects and higher vertebrates. The toxins complete formation externally with the addition of cations, and water quality variables such as salinity, temperature, pH, and nutrients influence the toxicity of a bloom. Algae control treatments have been developed for ponds and small reservoirs but are usually too costly and labor intensive for practical use on large water bodies. Potential treatments include ammonia compounds, copper compounds, acid applications, potassium permanganate, ozone, ultraviolet light, and nutrient manipulations. The decision to use treatments must balance expected benefits with costs and possible impacts to the aquatic ecosystem. Treatments must meet federal, state, and local rules and regulations and be coordinated with stakeholders. Research is ongoing to determine bloom dynamics and potential management options for large water bodies.

Introduction

Harmful algal blooms have occurred in reservoirs throughout the United States, and several taxa have caused toxic algal blooms resulting in fish kills and water quality problems. One species responsible for such problems is *Prymnesium parvum*, commonly called the golden alga, which was first described in 1937 in England (Carter 1937). *Prymnesium parvum* is widely distributed being found on every continent except Antarctica, reported from at least 14 countries, and is most often associated with estuarine or marine waters (Shilo and Aschner 1953; Larsen and Bryant 1998) but can exist in slightly brackish inland waters. *Prymnesium parvum* can form cysts when stressed (Green et al. 1982). Toxins released by *P. parvum* are called prymnesins and affect gill-breathing organisms (Yariv and Hestrin 1961; Ulitzer and Shilo 1966; Igarashi et al. 1999); however, most aquatic insects appear unaffected (Shilo 1972), and adverse

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impacts to higher vertebrates have not been documented (Linam et al. 1991).

Prymnesium parvum was found in brackish inland waters in the Middle East and caused fish mortalities in aquaculture facilities (Shilo and Shilo 1953). The alga was identified in the United States in water samples from a 1985 fish kill on the Pecos River, Texas (James and De La Cruz 1989; Linam et al. 1991). Since then, four additional Texas river systems, the Brazos, Canadian, Colorado, and Red, have had golden alga fish kills (Figure 1), and the alga has been reported in 16 states (Figure 2).

Since 2001, *P. parvum* has been a persistent problem in Texas, affecting 33 water bodies and killing more than 30 million fish, and communities associated with affected reservoirs experiencing losses in recreational-based incomes (Oh and Ditton 2005). *Prymnesium parvum* also is problematic in two Texas state fish hatcheries, killing broodfish and production fingerlings. As a result of these problems, Texas Parks and Wildlife Department (TPWD) started developing management options and coordinating research efforts concerning this toxic alga.

Starting in 2005, Arizona experienced *P. parvum*-associated fish kills in numerous Phoenix-area lagoons and three nearby reservoirs. The Arizona Game and Fish Department (AGFD) collaborated with industry, university researchers, TPWD staff, and other agencies to evaluate research and treatment studies. This collaboration resulted in development of

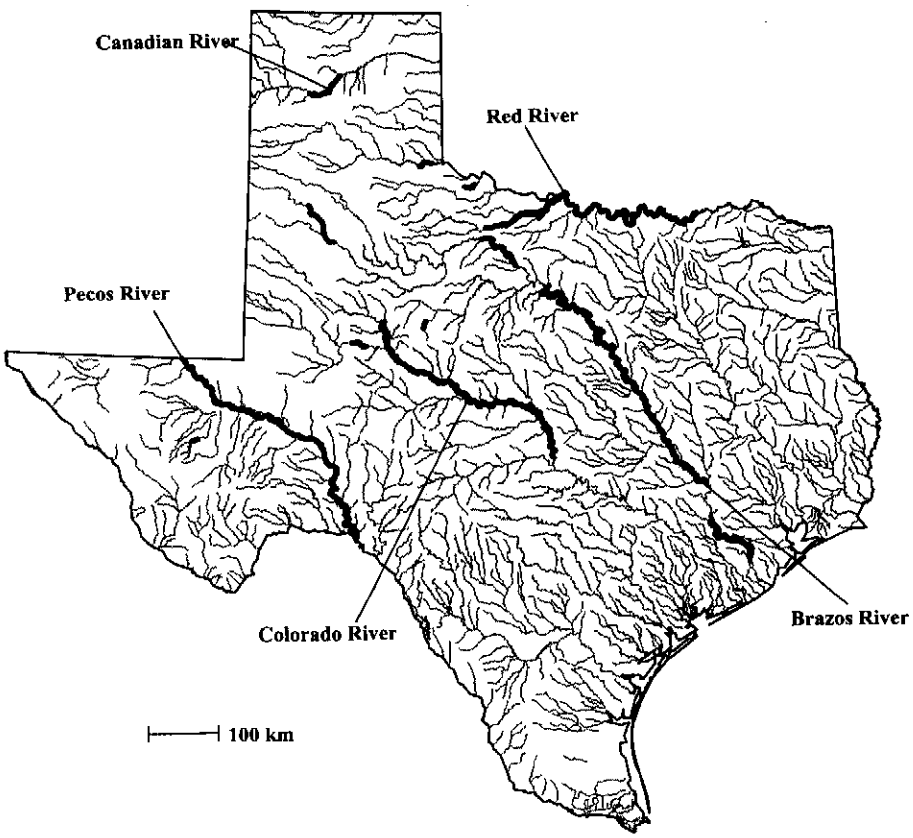

Figure 1. River systems in Texas with areas affected by golden alga fish kills depicted by dark shaded lines.

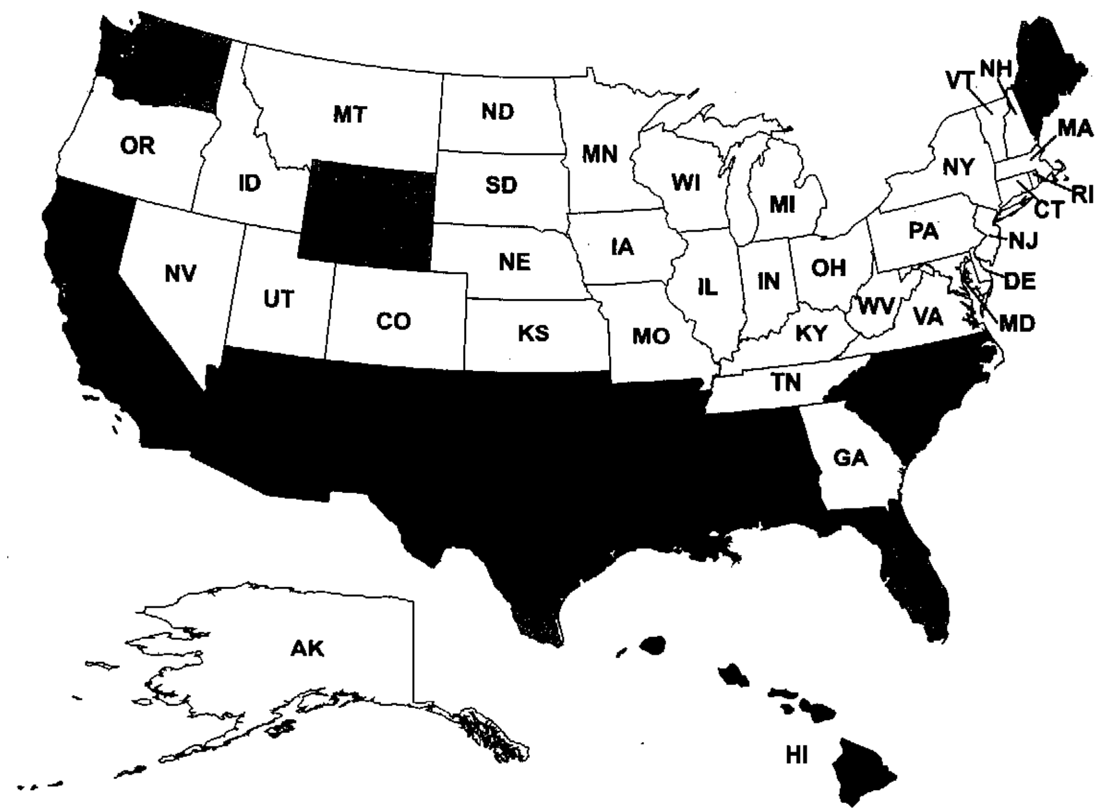

Figure 2. The states of the United States with golden alga presence reported (in dark shading).

a treatment and management plan for lagoons and small lakes by AGFD (Swanson 2006).

This paper compiles information on diagnosing *P. parvum* blooms and impacts to reservoir fisheries and related economies. Current treatment or management options are discussed.

Prymnesium parvum Blooms

Diagnostic Characteristics of Alga and Toxic Blooms

Visual indications of a dominant *P. parvum* bloom include abnormal yellow or gold to rust-colored water and foaming where the water is agitated. Stressed, lethargic, or dead fish may be present, with fish bleeding from the gills and showing reddening or hemorrhaging of the skin, particularly at the fins, opercula, mouth, and eyes. Affected fish also may generate a heavy mucus layer. Fish behavior can vary widely (Linam et al. 1991), and though fish typically swim slowly, lie on the bottom, or congregate near the shore, they may crowd around a freshwater source such as springs or actively leap out of the water onto the shore. Freshwater mollusks die and their soft bodies may be seen floating apart from their shells (James and De La Cruz 1989; Linam et al. 1991), while most adult and larval aquatic insects are apparently unaffected.

Microscopic examination of subsurface water samples is required since *P. parvum* is ultraviolet-light inhibited and avoids the water surface (Paster 1973), and magnifications of 400–1,000× are required for a presumptive identification. *Prymnesium parvum* (Figure 3) is subspherical to elongate

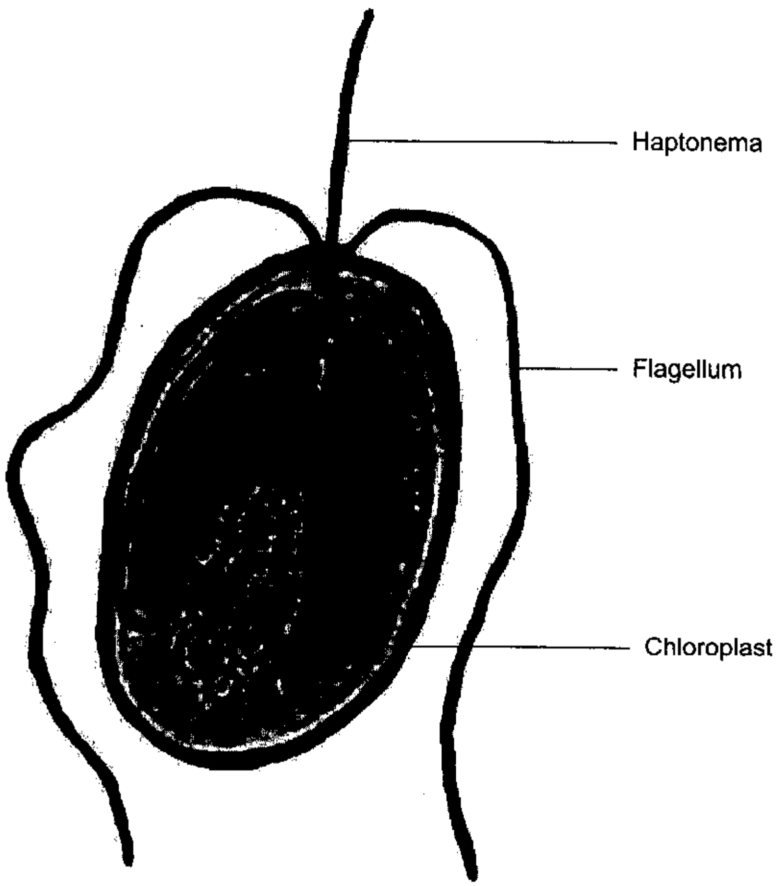

Figure 3. Golden alga cell with identifying characteristics indicated. (Drawing by Robert G. Howells, Texas Parks and Wildlife Department).

and approximately 8–11 μm long with two flagella and a haptonema arising from a pit (Lee 1980; Bold and Wynne 1985; Larsen 1999). The haptonema is flexible but non-coiling and can be used to attach the cell to a surface when the cell is resting. Two large yellow-green chloroplasts are situated laterally and parietally and are often deeply lobed. The alga exhibits a characteristic swimming motion of moving forward while spinning on its longitudinal axis (Green et al. 1982). Corroborative identification by experienced individuals is recommended when first becoming familiar with this organism, while confirmation of visual identifications requires the use of electron microscopy to examine scale morphology.

When stressed, the alga can form cysts that sink to the bottom sediments (Green et al. 1982). These cysts can be viable for several months and return to the normal cellular form when conditions are appropriate. However, cysts can only be accurately identified as *P. parvum* through electron microscopy examination of the cyst scales.

Factors Affecting Blooms and Toxicity

As with all phytoplankton, *P. parvum* needs a competitive advantage to increase in numbers and potentially dominate the algal community. Although the exact factors for *P. parvum* bloom and toxin formation are unknown and likely vary, there are several conditions commonly associated with toxic events. Investigations by TPWD indicate that most *P. parvum* blooms in Texas occur in the central and western areas of the state and begin during fall or early winter. Saline soils, natural brine springs, and oil field brines contribute to a high salt content in these areas of Texas. Lower temperatures associated with fall and winter and higher salt content could provide a competitive advantage for this euryhaline and eurythermal alga (Shilo and Aschner 1953; Larsen and Bryant 1998). Decreased populations of other algae and planktonic predators during winter result in less competition and predation and could contribute to *P. parvum* dominance, while other factors such as photoperiod and nutrient availability may be important but have yet to be determined.

Toxins released by *P. parvum* cells are not fully formed in the cell and must combine with cations in the water to form the final toxic compounds (Yariv and Hestrin 1961; Ulitzer and Shilo 1966; Shilo and Sarig 1989). Thus, water quality conditions greatly influence the toxicity of the final compounds (Shilo and Aschner 1953; McLaughlin 1958; Reich and Parnas 1962; Ulitzer and Shilo 1964; Shilo and Sarig 1989). One factor influencing the availability of cations to complete formation of the toxic compounds is pH (Shilo and Sarig 1989). At high pH levels, more cations are in solution and available than at low pH levels. Low pH levels can inhibit toxin formation. This is illustrated by *P. parvum* being present in many rivers and reservoirs across Texas but fish kills occurring only in central and western Texas. Soils in these western areas of Texas are alkaline and waters have pH greater than 7, while east Texas has acidic soils and lower pH (often below 7) in the associated water bodies where *P. parvum* can bloom without causing a fish kill.

Research indicates that nutrient concentrations also influence *P. parvum* toxicity (Dafni et al. 1972; Paster 1973; Holdway et al. 1978), with toxicity increasing under nutrient limiting conditions (Larsen et al. 1993; Johansson and Graneli 1999). The alga exhibits mixotrophy (Bold and Wynne 1985; Barreiro et al. 2005) and can acquire nutrients by consuming bacteria and other plankton. The toxin's allelopathic effect may be used to increase capture success by killing or slowing other organisms, and toxicity to fishes may be coincidental.

Due to the complex interactions noted, no correlation has been determined between toxicity, alga density, and toxin concentrations. High toxicity can result at low cell densities, or conversely, high cell counts can occur without toxicity.

Impacts to Aquatic Biota and Recreation

Ecological Impacts

Although a variety of toxic effects have been attributed to prymnesins, the ichthyotoxicity is best known (Shilo 1972; Paster 1973). Prymnesins affect gill-breathing organisms by causing hemorrhaging and interruption of the selective permeability of gills (Yariv and Hestrin 1961; Ulitzer and Shilo 1966; Igarashi et al. 1999). All species of fish, bivalves, crayfish, gilled amphibians (Paster 1973; James and De La Cruz 1989; Linam et al. 1991), and certain zooplankton species (Nejstgaard et al. 1995; Tillmann 2004; Barreiro et al. 2005; Kiesling et al. 2005) are susceptible to prymnesins.

Fish kill investigations in Texas indicate a general progression of fish mortality during a toxic bloom. Commonly, small forage fishes are initially killed, especially planktivorous species such as threadfin shad *Doroso-*

ma petenense and gizzard shad *D. cepedianum.* Freshwater drum *Aplodinotus grunniens* are affected relatively early during blooms. The next fish group impacted includes shallow-water fishes such as juvenile and young adult centrarchids, minnows, and cichlids. As the bloom expands and refugia disappear, larger, more mobile fishes, such as *Morone* spp. and ictalurids, succumb. Common carp *Cyprinus carpio*, gar *Lepisosteus* spp., and buffalo *Ictiobus* spp. usually are affected last. This sequence may vary according to the order habitats are affected by changes in water circulation carrying the bloom.

Ecological impacts depend on the duration and severity of the toxic conditions, with impacts ranging from minor reductions in forage fish populations to major declines in fisheries. Forage fishes are rapidly replenished through natural reproduction, while higher trophic species may require considerable stocking effort or years to recover naturally. Reservoirs with repeated fish kills have had their recreational fisheries essentially eliminated, and threatened, endangered, or species of concern may lack sufficient numbers to recover from kills. No risks to terrestrial vertebrate or human health have been documented for *P. parvum* toxins (Linam et al. 1991).

Secondary ecological impacts due to water quality degradation from factors such as dissolved oxygen fluctuations, high bacterial growth, and decaying fishes are possible. Alterations in the ecosystem community structure can result in impacts, including food web shifts such as reduced forage fish species, changes in phytoplankton species abundance, and increased bacterial abundance.

Economic Impacts

Fish kills have adverse effects on recreational economies associated with reservoirs and relate directly to reduced fishing success, poor esthetics, and perceived health concerns. In a study by Oh and Ditton (2005), *P. parvum* fish kills resulted in a conservative estimate exceeding $3 million U.S. dollars lost to the local economy around Possum Kingdom Reservoir. The study documented a significant reduction in visitation and concession sales at Possum Kingdom Lake State Park, which reflected losses from both decreased fishing and general use. The estimated economic loss did not include the value of the fishes killed, restocking costs, or relocation of fishing guides to other reservoirs.

Treatment and Management Options

Treatments for Hatcheries and Small Impoundments

Treatments to control *P. parvum* were first developed in Israel in aquaculture ponds using ammonia or ammonium sulfate to lyse cells (Shilo and Shilo 1953; Shilo and Sarig 1989). In laboratory tests, Shilo and Aschner (1953) mitigated prymnesin toxicity using substances such as oxidants, adsorbents, bacteria, and antibiotics. McLaughlin (1958) suggested a treatment by reducing pH to 6.0–6.5 to decrease toxicity, Reichenbach-Klinke (1973) found copper sulfate, a wide spectrum algaecide, to be effective, and Guo et al. (1996) recommended manure additions to prevent *P. parvum* dominance in fish culture ponds. Reducing salinity in brackish water ponds has been used to control *P. parvum* blooms (Guo et al. 1996).

To successfully rear sport fishes at affected hatcheries, TPWD has used, modified, and examined a variety of treatments (Barkoh and Fries 2005). Copper-based algaecides are effective at temperatures below 15°C but are nonselective towards phytoplankton communities. These algaecides may negatively affect important food sources and sensitive fish species. Impacts on other algae that are competitors to the golden alga need to be considered before using any wide-spectrum algaecide. Reducing these algal populations may actually give the golden alga a greater competitive edge to rebloom before the other algal species can recover. Ammonium sulfate additions increase un-ionized ammonia nitrogen (UIA-N), which causes osmotic imbalance leading to lysis of *P. parvum* cells (Shilo and Shilo 1962). The un-ionized fraction of total ammonia is positively correlated to temperature and pH, and treatments are not successful at temperatures below 15°C or pH below 7.0 (Barkoh and Fries 2005).

Texas freshwater hatcheries control *P. parvum* with a minimum concentration of UIA-N near 0.16 mg/L. This UIA-N concentration may have adverse effects on early life stages of fishes and sensitive fish species (Barkoh et al. 2003). Concentrations of UIA-N greater than 0.25 mg/L appear to have substantial negative effects on striped bass *Morone saxatilis* production. Monitoring pond pH, temperature, and ammonia concentrations is required to maintain UIA-N concentrations between these upper and lower thresholds. Two UIA-N treatment strategies are currently under evaluation at TPWD hatcheries. One strategy monitors cell densities and applies ammonium sulfate when *P. parvum* cells are found, while the other strategy maintains a minimum of 0.16 mg/L UIA-N at all times.

Concentrations of potassium permanganate near the potassium permanganate demand (Tucker 1989) may temporarily reduce acute toxicity due to *P. parvum* (Smith 2005a), and ≥ 2 mg/L above the demand may control cell density (Dorzab and Barkoh 2005; Smith 2005b). Hydrogen peroxide lyses *P. parvum* cells in 24 h at 62.5–500 mg/L, in 1 h at 3,125 mg/L, and in 15 min at 12,500 mg/L (Southard 2005). Higher concentrations can be used to disinfect equipment but may be harmful to some fishes (Rach et al. 1997). Additional studies on oxidizing compounds, especially those labeled as algaecides, are planned by TPWD.

In laboratory experiments, acid applications reduced pH, toxicity and density of viable *P. parvum* cells, but pH returned to pretreatment levels within 18–28 h (Southard and Klein 2005). Ultrasonic vibrations (Dorzab 2005), barley straw, and probiotics (e.g., bacteria inoculants) were studied but were not successful for control of *P. parvum* blooms and toxicity (Barkoh et al. 2008). For small water volumes, as in recirculating incubation systems and fish hauling units, TPWD has used ultraviolet light and ozone treatments to destroy cells and reduce toxicity. Ozone at 5 mg/L for 15 min is used to treat egg incubation and hatching system water at TPWD fish hatcheries. These treatments may not be practical for large water volumes.

Studies indicate that prymnesin toxicity may be related to nutrient limitation (Holdway et al. 1978; Kaartvedt et al. 1991; Aure and Rey 1992; Lindholm et al. 1999), and TPWD research suggests that nitrogen and phosphorus applications may control *P. parvum* cells and toxicity (Kurten et al. 2007). While nutrient enhancement shows promise, higher pH may result and must be addressed to make this a viable control option for areas with sensitive species. Nutrient manipulations may encourage bloom formation by other harmful algae such as blue-green species, so the nutrient ratios and algae must be carefully monitored.

When *P. parvum* was found in Arizona, the AGFD worked with universities and industry to examine treatment alternatives. A workshop held in 2005 led to the development of early detection and rapid-response guidelines for toxic blooms (Swanson 2006). The Arizona guidelines include algal control using copper-based algaecides (e.g., Cutrine Plus and Earth Tec) in intensively stocked and managed Urban Fishing Program (UFP) or private lagoons up to 20 ha.

The Arizona guidelines (Swanson 2006), the Texas hatchery management document (Barkoh and Fries 2005), and the Texas guidelines (Sager et al. 2007) provide an overview and possible treatment discussion for ponds and small impoundments. However, local regulations, water body-controlling authorities, chemical-use restrictions, lake-management objectives, and other issues must be considered prior to deciding upon a treatment option. These factors can require balancing competing needs or desires. Although several successful treatments have been found, these require monitoring for the presence and change in *P. parvum* populations, treatment levels, and the need for repeated treatment applications. Further, treatments may have undesirable side effects and may not be cost-effective for large water bodies. The need to balance the threat of the *P. parvum* with potential treatment problems should be addressed on a case-by-case basis prior to implementing these controls.

Treatments for Large Reservoirs and Lakes

Some research conducted or sponsored by TPWD was aimed at evaluating treatments for potential use in reservoirs. Clays and clay/flocculant combinations, which have been used against harmful algal blooms in marine environments, were evaluated for their efficacy against *P. parvum* (Sengco and Anderson 2005). While the six clays tested did not effectively remove *P. parvum* cells, removal was enhanced through adding flocculants with the clays. However, fish bioassay results were ambiguous, and whether the treatments reduced toxicity to fish species was undetermined. Additional research is required to demonstrate the feasibility of clay and clay/flocculant combinations. Barley straw and its extracts reportedly provide algal control without deleterious environmental effects (Gibson et al. 1990; Welch et al. 1990; Newman and Barrett 1993; Lynch 2002). However, TPWD-sponsored experiments failed to demonstrate efficacy of barley straw and its extracts against *P. parvum* (Kiesling et al. 2005; Barkoh et al. 2008).

Developing Management Options

To develop management options in Texas, TPWD initiated meetings to determine critical information gaps and, in October 2003, hosted an international workshop with experts invited from the United States and Europe to review the state of knowledge on *P. parvum* and discuss information needs (Singhurst and Sager 2004). Consequently, research was initiated to test treatment options, gain knowledge of bloom and toxin production dynamics, determine the alga's distribution in Texas, obtain genetic information, and conduct economic studies to determine impacts to affected recreational economies (Table 1). Overviews of this research and preliminary results are available through the TPWD Web site (www.tpwd.state.tx.us and search for golden alga).

To implement management plans in Texas, numerous stakeholders must be considered. Several agencies have responsibilities for problems associated with toxic *P. parvum* blooms in Texas waters. As the state fish and wildlife agency, TPWD is concerned with effects to aquatic ecosystems and recreational use. The Texas Commission on Environmental Quality, an environmental regulatory agency, is concerned with water quality and water-use issues related to the blooms. River authorities manage water-use activities and are concerned with how toxic blooms affect their operations and customers. Additionally, many local municipalities and businesses are affected by toxic blooms. This mix of state and local entities with vested interests in the affected aquatic systems dictates that management and control efforts aimed at *P. parvum* be well coordinated. When viable

Table 1. Research studies on the toxic golden alga undertaken or funded by the Texas Parks and Wildlife Department (TPWD; 2004–2007). More detailed information is available through the TPWD Web site (www.tpwd.state.tx.us).

Research topic	Research group[a]
Pond treatment options testing (copper, ammonia, ultrasonics, ultraviolet light, ozone, potassium peroxide, microorganisms, etc.)	Numberous TPWD researchers, including Aaron Barkoh, Gerald Kurten, Loraine Fries, Greg Southard, David Klein, Dennis Smith, Tom Dorzab, Dale Lyon, Jake Isaac, and John Paret
Barley straw treatment testing	Aaron Barkoh, John Paret, Drew Begley, Dale Lyon, Dennis Smith, J. Warren Schlechte, TPWD (Barley Straw); and Daniel Roelke, TAMU-College Station; James Grover, UT-Arlington; Richard Kiesling, USGS; and Bryan Brooks, Baylor University (Barley Straw Extract)
Lake Whitney golden alga bloom monitoring	David Buzan, Meridith Byrd, and Janet Nelson, TPWD
Statewide survey (distribution determination)	Loraine Fries and Greg Southard, TPWD
Removal from water column through clay and/or clay + flocculant application	Mario Sengco and John Anderson, Woods Hole Oceanographic Institute
Bloom and toxin production dynamics	Daniel Roelke, TAMU-College Station; James Grover, UT-Arlington; Richard Kiesling, U.S. Geological Survey; and Bryan Brooks, Baylor University
Impacts to regional recreational economy from 2001 Possum Kingdom Reservoir bloom and fish kill	Chi-Ok Oh and Robert Ditton, TAMU-College Station
Genetics (strain determination, qPCR [Quantitative polymerase chain reaction] development, etc.)	John La Claire, III, UT-Austin
Lake Whitney water circulation during blooms	Ayal Anis, TAMU-Galveston

[a] Abbreviations:
TAMU: Texas A&M University
TPWD: Texas Parks and Wildlife Department
UT: University of Texas
USGS: United States Geological Survey

treatment options are identified, TPWD will work with the other agencies and stakeholders to develop management plans and options. Guidelines were developed by TPWD to assist preparing plans and managing *P. parvum* blooms in Texas ponds and small reservoirs (Sager et al. 2007).

The treatment options developed for TPWD hatchery ponds (Barkoh and Fries 2005) may be applicable to small impoundments or partial treatments of large water bodies. Partial treatment of large water bodies may be practical to interrupt bloom initiation, control a bloom isolated to a smaller part of a larger water body, or perhaps establish refugia. Management options may vary based upon local conditions and could range from control of nutrient inputs to application of algaecides (Sager et al. 2007). Treatments likely will be implemented by local authorities due to the need for rapid response and the fact that local entities actually oversee the affected water bodies.

Since the majority of affected water bodies in Arizona are intensively managed urban impoundments, the AGFD developed a more aggressive approach to control *P. parvum.* In 2005, the AGFD held a workshop with experts from government, industry, and academia to discuss the problems and potential control strategies. From this workshop and *P. parvum* research and management results, AGFD prepared guidelines for management options for *P. parvum* in urban impoundments (Swanson 2006). These guidelines include information to minimize the risk of spread of algae, investigate and monitor toxic algal blooms, and control algae in UFP waters using copper-based algaecides, which are administered by professional lake consultants or park staffs. A monitoring program was implemented for the 20 UFP waters and several large impoundments on the Salt River with a history of algae problems (i.e., Saguaro, Canyon, and Apache reservoirs). The guidelines include communication and outreach strategies to keep the public informed. The AGFD will coordinate and monitor ongoing efforts for the state and revise guidelines as appropriate.

This paper covered activities undertaken in two of the affected U.S. states. We believe these collective experiences and knowledge gained may be helpful to any entity trying to develop management options for this harmful alga. While there are options to control *P. parvum* blooms in aquaculture ponds and small reservoirs, these treatments are not generally practical in large water bodies. Continued research may eventually identify control mechanisms for large water bodies affected by *P. parvum* by addressing the many questions and issues yet to be resolved.

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